Lithium metal for x−ray refractive optics

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ABSTRACT.

Lithium is the best material for refractive x−ray lenses because its x−ray absorption is the lowest of all solids. To test the application of lithium to x−ray lenses we have built a prototype of Cederstrom's saw−tooth refractive lens[1,2] (or alligator lens) from lithium. This paper reports the lens operation using the 10 keV x−rays on beamline 7ID at the Advanced Photon Source in Argonne National Laboratories. The lens performs satisfactorily, but not to its full theoretical potential. For example the lens gain is 3 while in this geometry the theoretical gain is 4.5. The difference is most likely due to surface roughness that is avoidable with more careful manufacturing techniques.

1: INTRODUCTION.

Optical propagation of x−rays is well known.[3,4] An electromagnetic wave with wave vector $\boldsymbol{k}$ and frequency w changes its amplitude $A(\boldsymbol{x})$ by the phase factor $\exp(-in\boldsymbol{kx} - iwt)$ as it goes through a material. The index of refraction n, or the dielectric constant n^2, includes the effect of secondary waves emitted by the material's electrons as they perform forced oscillations in the wave's electric field. For x−rays the index of refraction $n(\boldsymbol{k})$ is complex,

$$n(\boldsymbol{k}) = 1 - d - ib. \tag{1}$$

The term ib describes the exponential decrease of the amplitude, $A(\boldsymbol{x}) = A\exp(-b\boldsymbol{kx})$ and of the intensity, $|A|^2(\boldsymbol{x})= |A|^2\exp(-2b\boldsymbol{kx})$. The mass attenuation coefficient is $2b|k|$ and its inverse, the attenuation length, is $L= 1/(2b|k|)$. The attenuation comes from various processes, including inelastic scattering by the Compton effect (but because the photon energies of interest here is below 1 MeV, pair production does not occur).

Refraction comes from the term $d=d(\boldsymbol{x})$. It is

$$d = (f_1/2)(w_p/w)^2 . \tag{2}$$

For x−rays the refraction term d is small compared to unity, since the electron plasma frequency w_p ($w_p^2 = n_e e^2/\varepsilon_0 m$, with m and e the electron mass and charge, n_e the electron density, and ε_0 the permittivity of free space) is much less than the typical x−ray frequency. Absorption and refraction come from the forced oscillations of the material's electrons in the x−ray field. How the electrons are tied to atoms is represented by the atomic scattering factor f_1: for energies much higher than the absorption edge f_1 is close to the atomic number Z. The theory likewise relates optical attenuation b to a second atomic scattering factor f_2, and these two are tied to each other through causality. The Center for x−ray optics makes the numerical values for f_1 and f_2 conveniently available on its web site www−cxro.lbl.gov. For lithium at 10 keV, $f_1 = 3.001$ and $f_2 = 2.0176\text{x}10^{-4}$. Eqs, (1) and (2) then give $d = 0.96\text{x}10^{-6}$ and the attenuation $b = 0.064\text{x}10^{-9}$. Adding in the contribution from Compton scattering makes lithium's attenuation length 55 mm.

As in optics, a bi−spherical lens with radius of curvature R on both sides has a focal length $f=R/2d$. For x−rays d is so small that the focal length is very long: as an example, a single lens with R = 0.2 mm made from lithium focuses 10 keV x−rays at 100 m. The numerical aperture for a single x−ray lens is on the order of d, too small to be of much use in most applications. The outsize focal length and minuscule aperture made refractive x−ray lenses impractical[5] except for advanced synchrotrons.[6] As it happens, the highly directed x−ray beams from third−generation synchrotrons such as the Advanced Photon Source (www.aps.anl.gov), the European Synchrotron Radiation Source (www.esrf.fr), and the Super Photon ring (www.spring8.or.jp) match the long focal length and the small aperture of refractive x−ray lenses quite well. Long distance focusing on these x−ray sources, under conditions when bent mirrors or Fresnel lenses are problematic, could be attractive even with a single x−ray lens.[7] A detailed comparison of refractive lenses with alternatives such as curved glancing incidence mirrors or Fresnel lenses seemed to come out in favor of the latter, even if the focal length could be halved by putting two lenses in series.[8]

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In 1996 Snigirev et al demonstrated[9] how to bring the x−ray focal length down to human scale, by putting not two[8] but many lenses in series. This is the compound refractive lens (CRL). Snigirev's first one−dimensional lens consists of a row of 30 small holes drilled in an aluminum strip. The focal length comes out as 1.8 m, 30 times less than for a single lens. Since then many groups have demonstrated compound refractive x−ray lenses, from materials such as silicon,[10] aluminum,[11] plastics[12] and beryllium,[13] and even with a row of bubbles in liquids.[14] Notably at the ESRF the x−ray refractive lenses are in routine use: plastic and beryllium lenses are commercially available.[12,13]

The principal difference in designing lenses for the optical versus the x−ray regime is absorption. This is dominant for x−rays, negligible for common optics, sometimes a useful feature in the infrared, and problematic for short microwaves.[15] Lenses made from materials with well−developed forming capabilities such as silicon, aluminum, and plastics achieve close to theoretical performance. Beryllium is theoretically an excellent material for lenses intended for the lower end of the x−ray energy regime of interest, say from 4 to 15 keV, but to our knowledge the literature does not contain equally good experimental data. Even so, beryllium with a row of holes works well enough as a lens that these lenses are used at various synchrotrons.

As the best material for x−ray refractive lenses beryllium is eclipsed by lithium, especially at the lower photon energies. In this region lithium's mass attenuation coefficient is the lowest of all solid materials. A good figure of merit for x−ray lens materials is the ratio d/b, or equivalently, the critical Fresnel number[8] $N_0 = d/(2\pi b)$: this is the number of phase reversals per attenuation length in the material minus those over the same distance in vacuum. For lithium at 10 keV $d/b = 15{,}000$ and the critical Fresnel number $N_0 = d/(2\pi b) = 2400$. For the next−best material, beryllium, $N_0 = 550$, while for the plastics the critical Fresnel number is still lower (polypropylene has $N_0 = 220$ and polyimide (kapton)[12] has $N_0 = 121$). Lithium's fourfold advantage in the critical Fresnel number over beryllium and order of magnitude advantage over plastics makes us go after x−ray refractive lenses from lithium, since all the desirable lens properties such as the gain and the width of the diffraction−limited focal spot become better with increasing N_0.

The only difficulties in implementing x−ray lenses from lithium metal are practical. Lithium metal is quite common in its own specific niches in research and industry, e.g., lithium batteries and in steel and chemical manufacturing. Here it is prized for its high chemical reactivity. This same property makes lithium hard to handle in other applications, where reactive metals that burn in water are usually problematic. However, lithium is easy to handle in vacuum or in an inert atmosphere, and when coated with parylene it can even be exposed to normal laboratory air, at least for a limited time.[16]

Another problem is to get it into the right shape. Lithium is too soft for the usual metal fabrication processes, but it is easily formed by pressing it into suitable molds. In short, lithium can be handled without too much difficulty once the right equipment is available, at which point it can be coated with parylene to enable further handling in a laboratory setting.

This paper shows the performance of one prototype lithium lens. For manufacturing ease this lens uses the sawtooth geometry first suggested by Cederstrom.[1] It consists of two rows of prisms placed in the beam under a slight angle. The prisms are one−dimensional, so that the lens focuses in one dimension only. Despite its simplicity and ease of manufacturing the lens is very handy: in particular, the focal length can be adjusted by changing the angle with the x−ray beam. A memorable name for this type of lens is 'alligator lens' because that is what it looks like.

Figure 1 shows a 45 mm long section of one 'jaw' with 30 lithium teeth. The teeth are 6.3 mm wide, 1.5 mm apart and 0.75 mm high. They are fixed in a brass mold whose edge is visible on the top left and bottom right. The teeth are nice and straight, but not perfectly sharp. The photograph shows one dark stripe betraying contamination of the lithium surface in the center parallel to the jaw, and similar contamination close to the brass holders. Not discernible in the picture is the roughness of the surface: to the eye the teeth are quite smooth, but the actual roughness is on the order of 5 micrometers rms. The actual lens is longer than can be shown in this photograph: it has 80 teeth over its 120 mm length.

The results with this lens are promising, but not yet final. Focusing of 10 keV x−rays by a single jaw of the alligator lens gives a threefold gain in intensity. The gain is 30 % lower than expected from the geometrical defocusing and the attenuation in the lithium. The difference is attributed to manufacturing imperfections, mostly to an excessive roughness but little to rounding of the teeth. It seems straightforward to avoid these problems in the x−ray lenses to be built and tested in the future.

For the moment the threefold gain is enough to make time−resolved experiments on the 7ID beamline easier and faster. Its first use was during June 2001, a month after the present test.

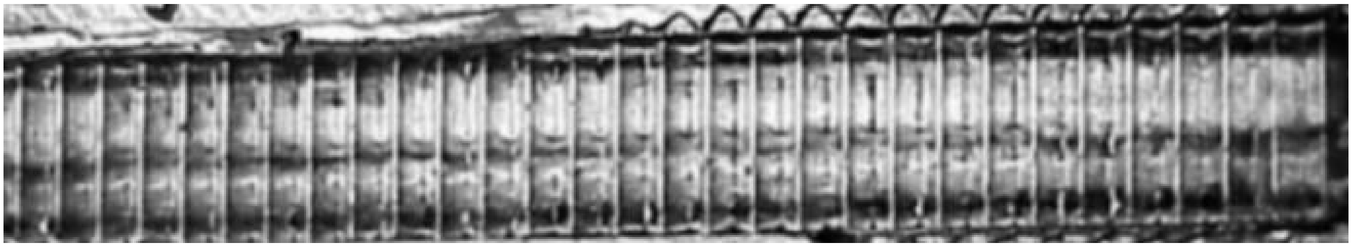

Figure 1: Part of a 'jaw' with lithium teeth.

The remainder of this paper presents our measurements on the lithium x−ray lenses in more detail. Section 2 summarizes the important points for refractive x−ray lenses, and the alligator lens in particular. Section 3 describes the experimental setup and discusses the measurements. Section 4 mentions directions for future work. Although various CRL developers have considered[17] using lithium, there are to our knowledge no other experimental results on lithium x−ray lenses.

2: THEORETICAL CONSIDERATIONS.

Diffraction theory for x−rays including Eqs. (1) and (2) is well−known,[3,4] and so is the design of refractive lenses in general.[11,18] This section contains only some points that are relevant to the present test of an alligator lens from lithium.

Figure 2 shows an idealized geometry for a single jaw of the alligator lens. For clarity the figure contains two panels, one to show the deflection and the second to show the attenuation. There are only two teeth. Each has a 90 degree top angle, as in the lens of Figure 1. This choice of angle is driven by ease of machining: any other angle is difficult to make with a standard milling machine.

In Cederstrom's paper[1] the focal length follows from the alligator lens' parabolic density profile. An alternative[2] calculation is to consider the beam being bent by the individual teeth, or prisms, as follows. In Figure 2a the rightmost tooth deflects the x−rays over a (small) angle a, shown much exaggerated in the figure by the break in the dashed curve. The lower panel shows the dashed line as the center of a thin x−ray beam slice, with height h. Three beam slices with the same height h comes from a point source at infinity from the left. The first beam passes over all the teeth: it is not deflected. The beam next to it deflects only in the right−most tooth, over an angle a. It crosses the first beamlet at a focal distance $f= h/a$. The third beam slice displaced a distance $2h$ below the first beam slice passes through two teeth. Therefore it is deflected over an angle $2a$. This third beam still intersects the first beamlet at the same focal distance $f= 2h/2a = h/a$. Likewise for all the other beam slices: for M teeth all the M beam slices intersect at the same focal distance $f= h/a$. A tooth with a 90 degree top angle bends the beam by an angle $a=2d$. Then, the focal length $f=h/2d$.

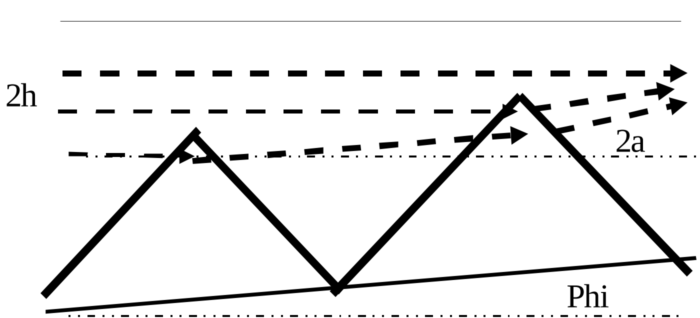

Figure 2a. Two teeth in one jaw of the alligator lens slicing the x−ray beam. The deflection angle is very much exaggerated.

The focal length $f=h/2d$ is easily adjusted. All you have to do is change the height h of the beam slice. The height is simply $h=p\Phi$, the distance between subsequent teeth or the pitch p, multiplied by the (sin of the) angle Φ between the teeth and the beam. The angle is limited by the lens aperture A, which is at most the tooth height. For the lens here, where the top angle of the tooth is 90 degrees, the height of the tooth is *p/2* which is also the maximum aperture. Therefore Φ is at most *1/2M*. Note that the maximum aperture does not depend on the tooth pitch. For the lens here, with *M*= 80 teeth, the maximum angle is 6.25 milli−radians or 0.36 degrees. At this angle the height of a beam slice is minimal, $h=p/2M$, and the closest focus is at $f=p/(4Md)$= 4.6 m.

If the x−ray source is at infinity, and all the x−rays in the initial beam are parallel, all the beam slices keep the same height down to the focal spot. In the focal spot the intensities of the *M* beam slices together add up to *M* times the initial intensity, at least if the different beam slices are uncorrelated, and if there were no attenuation in the teeth. In this ideal case the gain *G* is the number of teeth hit by the beam, $G=M$. For a non−ideal situation the gain is of course lower. The principal corrections are absorption in the teeth, and beam divergence.

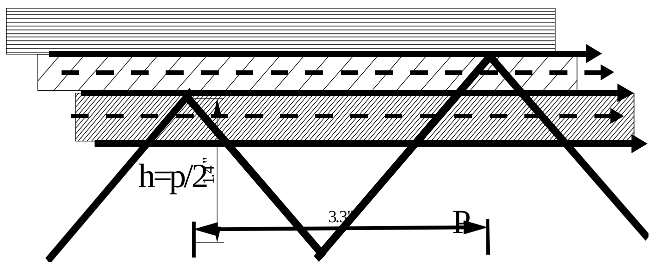

Figure 2b: Beam slices and their attenuation in the teeth.

Figure 2b illustrates the absorption of a beam slice by a tooth. The top slice passes over the teeth, so there is no attenuation. Transmission of the second slice through a single tooth is $T=\exp(-l/L)$, where *L* is the attenuation length and $l=h=p/2M$ is the path length of the slice through the tooth (it is a single dash in Figure 2b). The third slice goes through a second tooth, where the path length is 3 dashes, or *3l*. The total path length through the 2 teeth is then *4l*, and the transmission factor is T^4. Likewise, the path through the i−th tooth is $2i+1$ times that through the first tooth, and adding up the path lengths through all the teeth up to *i* makes the total path length proportional to i^2. This is of course the expected parabolic profile.

Attenuation in the lens is calculated as follows. Beam slice *i* reduces its intensity by a factor T^j where $j=i^2$, or equivalently, a factor $\exp[-i^2\ln(1/L)]$. Good transmission of x−rays through a single tooth implies *T* close to unity, and small per−tooth attenuation $(1/L) = p/2ML$. For the lens here the distance between teeth is p=1.5 mm, the attenuation length is on the order of L = 60 mm, and M = 80. Then the per−tooth attenuation $(1/L)$ = $1.56\text{x}10^{-5}$. The beam slice that goes through all 80 teeth sees half the thickness of the lens. This happens to be the attenuation length, so that this outermost beam slice attenuates by a factor $1/e$=0.37. Adding all the beam slices gives for the attenuation factor $\Sigma\exp[-i^2(1/L)]$, where the summation runs over the number of slices, from 1 to 80. On replacing the sum by the integral this becomes $\int\exp(-x^2)\,dx$, where the integration limits are from x=0 (for the beam slice at top of the teeth) the x=1 (for the beam slice through 80 teeth). Expanding the exponent and integrating the resulting sum gives 0.75. The measurement is about the same, 0.8.

The second factor in the gain is the finite size of the source, or equivalently the divergence of the beam. Without absorption the gain is the inverse of the magnification. Here the source with 0.8 mm FWHM is located 49.2 m upstream of the lens, and the measurement position is 6.9 m downstream. The maximum gain is then 7.1. Absorption in the teeth reduces the gain by a factor 0.75, to 5.3. The measurement suggests slightly more than 3.

The lower gain is probably due to manufacturing imperfections in the teeth. Up to now the teeth are assumed to be ideal, that is, they have a sharp top, all the teeth are perfectly lined up, and they are all perfectly smooth. This lens' teeth in Figure 1 seem to be lined up nicely, but they are certainly not sharp, and how smooth the surface is can not be seen here. Inspection through a microscope (without camera, unfortunately) shows a roughness that is consistent with machining marks on the mold. The molds to date have the best surface quality[19] that can be expected from conventional machining or grinding, quoted at about 1 micron rms. Calculations[20] can estimate the effect of surface roughness−induced phase changes on the focal spot, but it is better to show them directly with one of the x−ray measurements to follow.

Perfectly sharp teeth are hard to get with molding, because the lithium can not easily flow into sharp points. Figure 1 suggests a radius of curvature that is a small fraction of the tooth height, perhaps 5−10 % or something like 10−s of microns. X−rays passing through the round top of a tooth, as in Figure 3, deflect over an angle

$$a=2d\ \mathrm{tg}(\Theta/2), \tag{3}$$

where Θ is the angle formed by the tangent to the tooth where the x−ray goes through. At a round tooth Θ is larger than 90 degrees, so that an x−ray through the top of the tooth bends more than an x−ray through the tooth’s body. However, only a few of the beam slices go through the top of the tooth, and part of these slices continue to overlap the other slices in the focal region when the beam is not perfectly parallel. Therefore, the effect of tooth roundness on gain is relatively minor. A reasonable estimate is to subtract half of all the beam slices that pass through the round top. A further correction may be the extra attenuation of the first beam slice that is just under the round top, compared to the beam that would otherwise go through a sharp top. In any case, the effect of tooth roundness on gain is relatively small.

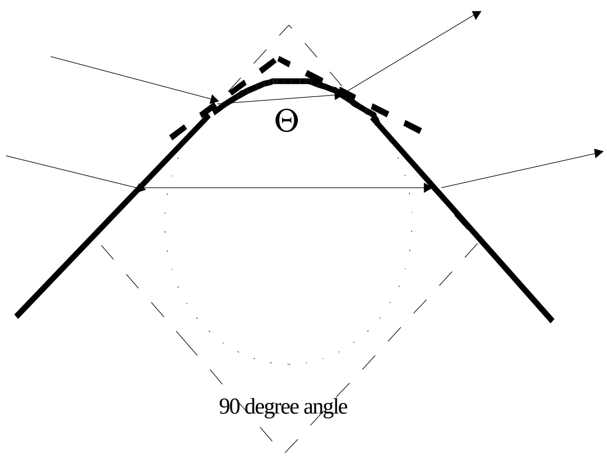

Figure 3: Close−up of one (rounded) tooth.

The gain estimates up to now use lithium’s theoretical x−ray absorption. In any low atomic material, including of course lithium, x−ray absorption is quite sensitive to higher atomic number impurities. Table 1 lists the impurities given in the lithium manufacturer’s certificate of analysis, their (weight) percentages, and the additional percentage x−ray attenuation these impurities give for 10 keV x−rays. All the impurities together add up to just over 0.02%, but they attenuate the 10 keV x−rays 2 % more than pure lithium without any contaminants. Clearly, impurity absorption is no problem.

Element	% impurity	% attenuation increase (at 10 keV)
N	0.0140	0.16
Na	0.0028	0.13
Cl	0.0020	0.34
K	0.0022	0.51
Ca	0.0029	0.79
total	0.0240	1.93

Table 1: Bulk impurities in sample high purity lithium.

Surface impurities are may be more important than those in the bulk. Lithium’s surface always has a thin layer of protective oxide, and the (black, nitrogen) corrosion on some parts of the teeth in Figure 1 is a visible reminder that the lithium in this lens may be less transparent than theoretically possible. An x−ray passing through a tooth goes through two surfaces, both under an 45 degree angle. The path length through all the surface layers of the M teeth is therefore $2M\sqrt{2}$ times longer than whatever contamination is in a single layer. How important these many surface layers is unknown at this time, but they can only increase the attenuation. In addition, this particular lens could have surface contamination entrained into it by the fabrication process. The prototype lenses here are molded from lithium that is made 1 mm thick by compacting 8 layers of 0.125 mm thin lithium together.

A thin layer of parylene−N on top of the lithium can delay lithium's corrosion in normal air. Parylene's applicability to x−ray lenses is demonstrated by one lens prototype covered by a 0.3 micron thick coating. The coating adds 0.068 mm through parylene−N to the x−ray path length. Parylene−N's attenuation length at 10 keV is 4.3 mm, making the extra attenuation through the parylene an acceptable 1.5 %. The coated lens performed well enough, but its gain was lower than the lens highlighted here. Measurement of the attenuation at 10 keV in the next section gives for the lithium in one actual lens an average attenuation length of 58 mm, close to the theoretical value of 55 mm from NIST.

Deliberate surface coverage with parylene−N adds only a little to the attenuation, so it is difficult to understand how unintentional surface impurities can account for the extra attenuation. Surface contamination is, in any case, avoidable by more careful lithium handling. The same should be true for small angle scattering off a rough surface. At the moment the scattering seems to be the dominant factor that could cause the gain to be lower in the experiment than it should be.

3: EXPERIMENT.

The focusing tests are performed with 10 keV x−rays from the double crystal monochromator on the 7ID undulator beamline of the Advanced Photon Source, operated by the University of Michigan, Howard University, Lucent Technologies−Bell Labs Collaborative Access Team (MHATT−CAT). The horizontal source size is 0.8 mm FWHM. A white beam slit 26.5 m from the source collimates the beam to 1 mm horizontally and 0.5 mm vertically.

The lens is 49.2 m from the source. A second slit 75 mm upstream of the lens limits the beam to 0.7 mm, less than the 0.75 high teeth in the single jaw under test. The aperturing avoids blurring of the focus from x−rays beyond the parabolic approximation valid for the alligator lens. With two jaws the aperture could be twice as wide to allow x−rays into the second jaw. The lens then passes twice as many x−rays, and if these end up in the same spot the intensity there doubles.

The x−rays are observed by looking with a Qmax 650 CCD[18] at the fluorescence in a 0.5 mm thick YAG:Ce−doped single crystal. The measurement is linear in x−ray intensity: its resolution is 0.02 mm or about 3 pixels FWHM.

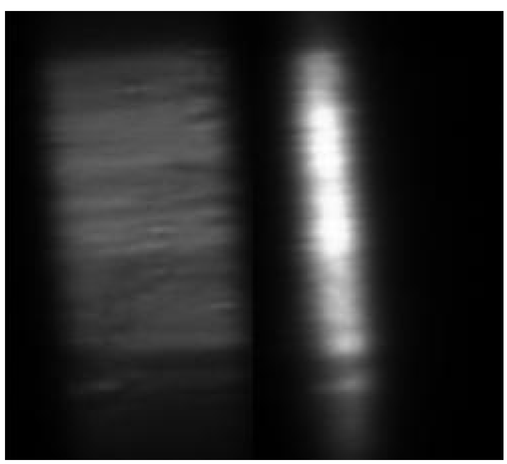

Figure 4: X−ray beam intensity. To the left is the original beam, to the right is the focused beam.

The lens housing is a high vacuum cross with 2 3/4 inch Conflat flanges 70 mm in diameter. It can be evacuated with a turbopump, and then maintained at 0.1 mPa with an ion pump. The housing is mounted on a 4−axis motion stage that allows precise control over the positioning from a remote location. Vertical (y) adjustment puts the 1 mm high beam at some suitable position along the 6 mm high teeth of the lens. In the horizontal (x) direction the lens moves into and out of the beam, with micron precision.

The other two axes allow turning the lens with respect to the beam. Turning around the beam (z) axis allows lining up the lens teeth with the vertical beam edge. The lens should focus the same amount over the entire beam height if this adjustment is done properly, and the geometry is purely one−dimensional. Focusing takes place in the y direction by turning the lens around the y axis.

Figure 4 shows a typical result achieved with the lens. To the left is the intensity of the initial beam. It has some horizontal striations that are related to phase shifts in the various kapton and beryllium windows in the beam path, but it is otherwise fairly uniform in the horizontal direction. The beam is is limited by a 0.7 mm aperture 6.5 m away: at the scintillator the beam is 0.82 mm wide. Vertically the beam is roughly a Gaussian. The right side in Figure 4 is the focused beam. The x−rays on the right side of the original beam have gathered to the left, where they are now concentrated into a 3−4 times smaller region. The peak intensity along the focal lines is about 3 times higher than in the original beam. The striations in the original beam are also visible in the focused beam, in some average sense.

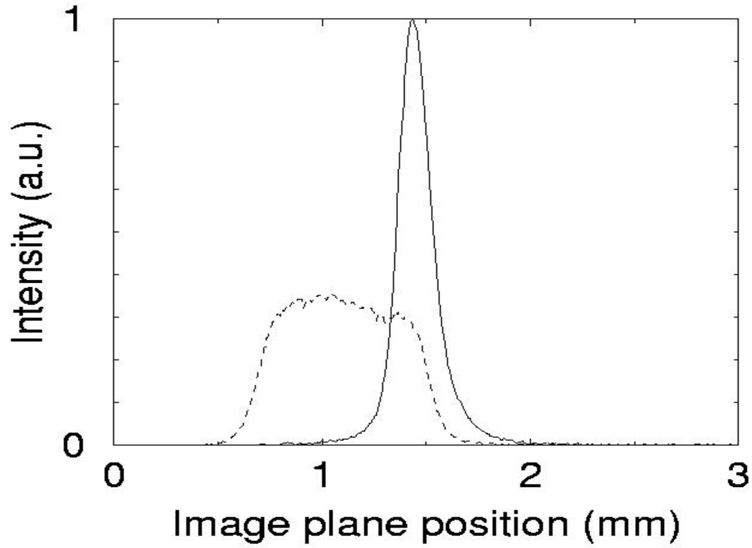

Figure 5: X−ray intensity in the unfocused (dashed) and focused (solid) beam measured 2 m farther downstream than in the picture of Figure 4 (at 8.5 m).

Figure 5 compares cross sections at mid−height through similar x−ray beams as in Figure 4. The low, wide curve is the initial beam intensity, the peaked curve the focused beam. For this cross section the peak intensity in the focused beam is about 3 times larger than in the initial beam. Other cross sections are qualitatively similar but differ quantitatively, as is also clear from Figure 4. Putting the 1 mm high beam higher or lower on the 6 mm wide lens gives very much the same focusing, although the gain is slightly lower than shown here but always more than 3.

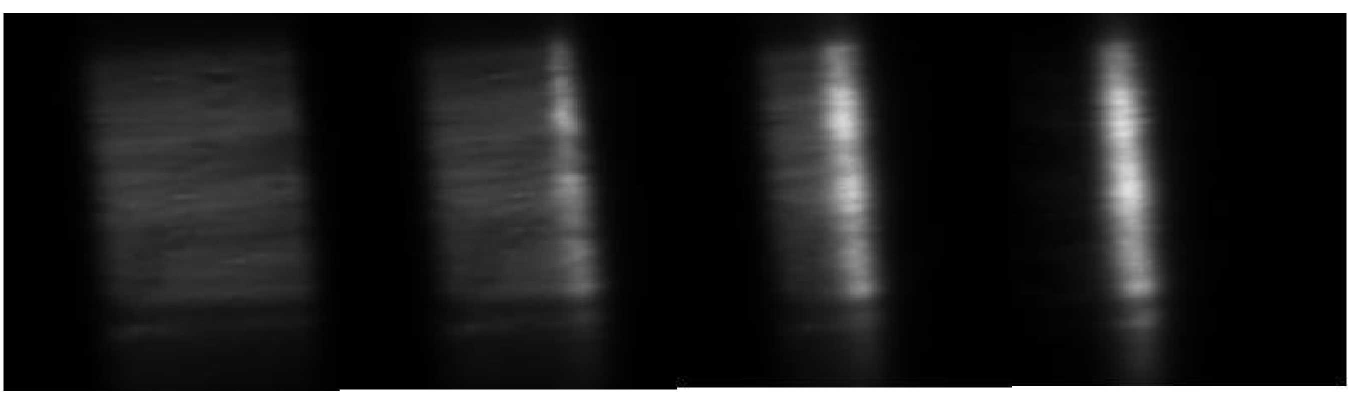

Figure 6: Piling up of the x−ray intensity with the lens teeth.

Figure 6 shows the x−ray pattern for partial focusing, that is, when the teeth intercept only part of the beam. To the left is the original beam, and to the right the fully focused beam. In between is the intensity pattern when the lens is 0.2 mm and 0.4 mm into the beam, coming in from the right side. As the teeth move into the beam, the x−rays deflect over an angle that is proportional to the number of teeth they go to. For Figure 6 the lens is under the optimum angle, so that the deflection is also proportional to the lens position with respect to the beam. Therefore, the x−rays seem to pile up on the left side of the original beam, away from the lens teeth.

Many similar measurements with this lens and other lens samples give results that are very similar to those in Figures 4, 5 and 6. Sometimes differences can be traced back to special properties of the specific lens. For example, post−test inspection shows that one lens has very visible corrosion on the surface. For this lens the gain is about two. The lithium in another lens is protected by a 0.3 micron layer of parylene that makes it possible to handle the lens in normal atmospheric air. This lens has a gain of 2.6, about 20 % less than the lens whose results are shown in Figures 4−6, which has no parylene coating. An estimate of the absorption in the parylene suggest that the coating subtracts only a few percent from lithium's effective transmission. Therefore, the lower than expected gain of this parylene−coated lens must come in part from individual variation in the lenses.

It is difficult to quantify manufacturing imperfections such as rounding and straightness of the teeth, and the teeth's surface quality. However, the imperfections are immediately seen with the x−rays. Figure 7 is one example. It compares the intensity patterns of x−ray beams apertured to 29 microns as transmitted symmetrically through all the teeth, parallel to the top of the teeth. At the measurement location the beam by itself, without interacting with the teeth, widens to 35 micron, but once the beam goes through the teeth the beam widens substantially. In the ideal case the beam deflects by the same distance $2Mdf$ = 1 mm parallel to itself over the entire beam height as soon as the beam hits the top of the teeth. With this lens the beam deflects gradually as it first encounters a tooth, then it bends more and more. Once the beam goes through all the teeth, the average deflection is indeed about 1 mm, confirming that lithium's index of refraction decrement is close to the theoretical value. However, the beam does not deflect exactly the same amount at each point, resulting in a sinuous movement of the beam spot as the lens moves up and down though the beam. The sideways shifts in beam position are suppressed in Figure 7, which emphasizes only the intensity pattern. Sometimes the beam projected by the teeth of the lens is three times wider than the original beam, but in any case the intensity depends on where the beam goes through the lens. As with the center of the beam, moving the lens up and down changes the beam's striations in the vertical direction.

The data in Figure 7 demonstrate that the lithium teeth as seen in Figure 1 are not yet good enough for the lens to behave as intended. Wiggling and widening of the x−ray beam as it passes through the teeth reflects phase changes caused by small−scale variations in the surface, which are clearly too large to make a good lens. Better surface quality of the teeth is the solution.

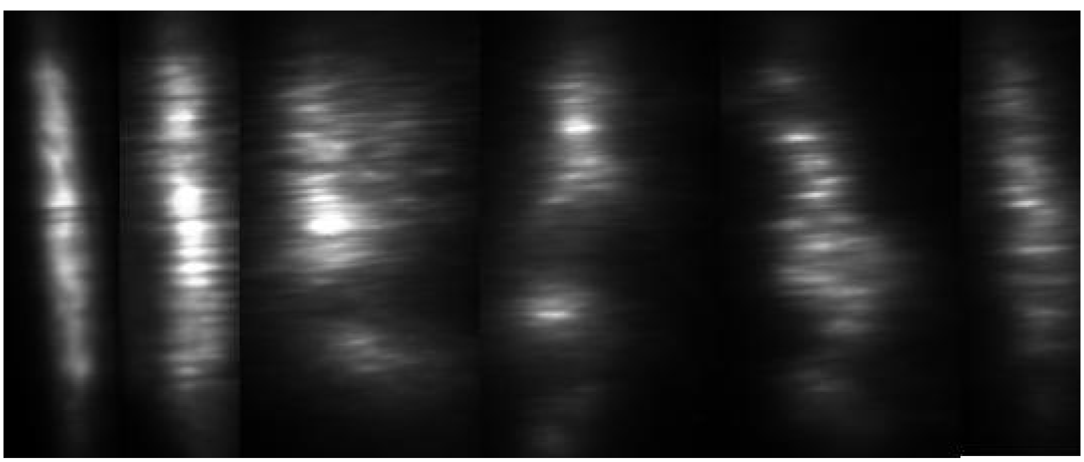

Figure 7: A 0.029 mm thin beam transmitted by the lens teeth. To the left is the original beam. The 5 other images are the beam transmitted from 0.1 to 0.5 mm below the top of the teeth (in steps of 0.1 mm).

Figure 8 is the same measurement done with a shorter lens made with a smoother but smaller die whose teeth were made by putting microscope slides under a 45 degree angle. Glass surfaces are very smooth, often better than 10 nm rms and in this case three orders of magnitude smoother than machined surfaces. The lens made with the glass die has only 25 teeth.

This shorter lens deflects the beam less than 1 mm, as expected, but with these teeth the beam width increases very little. Also, the wiggles in the beam are gone. This measurement corroborates the conclusion about surface imperfections of the teeth as culprits for the reduced performance of the lens in comparison with theoretical expectation.

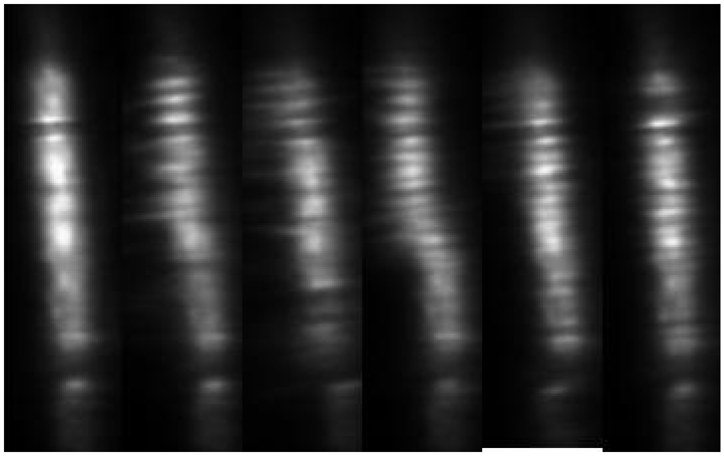

Figure 8: A 0.029 mm narrow beam transmitted to lithium teeth made with a glass die. The surface quality of these teeth is much better than the teeth made with a machined die.

The same experimental setup allows a direct measurement of the attenuation in the lithium. The beam intensity is measured quantitatively by an ion chamber at 50 mm behind the lens. This close to the lens the beam has not yet deflected, but enters and exits the ion chamber through the same point on the windows. The ion chamber is insensitive to changes in beam phase that give such variation local beam intensity at the scintillator. As the lens is pushed into the thin beam, the current in the ion chamber decreases exponentially. The decrease is consistent with a 58 mm attenuation length of 10 keV x−rays in the lithium.

Although some lenses came out better than others, each of the lenses seems to be stable over time. In fact, the data from the one lens that provides Figure 4−8 does not seem to change at all in a month of use. Once the lens position is optimized the focus remains at the same spot, at least if the initial photon beam is stable enough.

4: CONCLUSION.

The results here demonstrate that lithium is a viable material for x−ray lenses. The focusing shown by the lithium agrees with theory, while the gain is lower but for understandable and most probably avoidable reasons. The lenses can then be designed satisfactorily using the known x−ray parameters of lithium. It is also clear that fabricating the lenses is still needs more work. Areas of concern are surface impurities, which reduce lithium’s transparency, and surface imperfections, which reduce the lens’ quality. Both can and will be improved in future work.

The alligator lens tested here is attractive for the intended application on the beam line. It is easy to manufacture, and its focal length can be adjusted. However, the alligator lens is not optimal for increasing the x−ray intensity. The lens focuses in one dimension only. The two alligator lenses needed for two−dimensional focusing demand twice as much adjustment, which is time−consuming and expensive because it needs twice as many motion stages. Adjusting the focus by changing the lens orientation is convenient, but not essential: the focal spot from a lens with fixed focal length can be brought to the desired illumination point by changing the position of the lens, closer or farther away from the image point to bring it into focus. Therefore, further work will also consider parabolic compound refractive lenses as already implemented with much success[11] in aluminum.

5: ACKNOWLEDGEMENT.

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19: Interestingly, lenses for x−rays are quite similar in their phase change per unit length, *kd*, to lenses in the infrared. Of course the spatial scale for the roughness that scatters the most is orders of magnitude larger for the infrared than for x−rays.

20: Small−angle scattering is a field in itself. In the context of x−ray refractive lenses it has been discussed by Ref. 11 and 12. In their formulation scattering effectively adds a term to the absorption. We do not have independent measurements of the roughness to evaluate these expressions.